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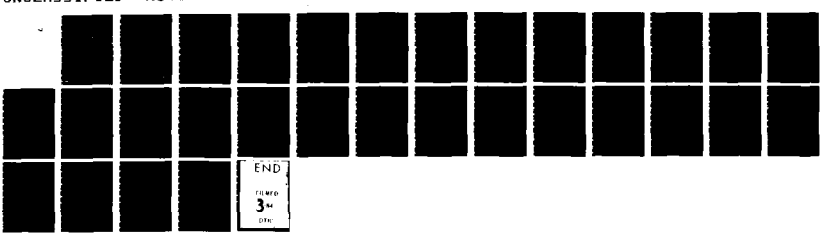

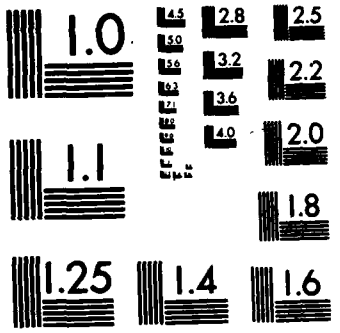

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PART VIII CHAPTER 194

CRANIAL DEFECTS AND CRANIOPLASTY

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INTRODUCTION

The cranium is the province of the neurosurgeon who must respect and be knowledgeable of its unique biological nature no less than the brain itself. Craniotomy for various cerebral lesions requires safe passage to and from cephalic areas with eventual restoration of conformity of the head. The temporary exteriorization of sections of the skull either free or hinged on a muscle pedicle in every craniotomy is followed by a form of fresh autogeneic (formerly autogenous) cranioplasty. Discontinuity defects of the cranium for which there is no replaceable skull section have engaged the ingenuity of surgeons from antiquity to the present. The problem of reconstructing the smooth symmetrical and rounded contours of the skull is complex, the moment of accomplishing this is often fleeting, and the diversity of methods advanced through the years testifies to the unsolved nature of this Sisyphean task.

BRIEF HISTORICAL REVIEW

Operations on the cranium long antedated procedures on the brain (46). Primitive races trephined to let out devils by scraping away bone until dura was exposed. Coconut shells were used by South Sea Islanders to repair the defect. Petronius in 1565 used a gold plate to repair cleft palates in the first instance of an alloplastic material to repair a defect. J. van Meekren in 1670 is credited with the first bone graft in history when he used canine bone to repair a skull defect in a Russian, but removed the implant under threat of excommunication by the church. Merrem in 1810 transplanted bone in dogs and in 1821 P. von Walther performed the first human autogeneic

bone graft. The work of Ollier in 1859 established the importance of periosteum in bone regeneration. Macewen in 1873 reimplanted calvarial bone fragments after treating them with bichloride of mercury and in 1878 was the first to transplant a human bone allograft (9).

Senn in 1889 wrote on the repair of cranial defects with antiseptic decalcified bone. In that same year Seydel transplanted an autograft of tibia with attached periosteum to repair a parietal defect. Müller and König in 1890 independently advocated a flap of scalp periosteum and outer skull table to be swung over a skull defect. Bunge (1903) first used fresh osteoperiosteal homograft (allograft) skull. The work of Siccard, Dambrin and Roger from 1917 to 1919 introduced cadaver skull in cranioplasty. The transplantation of fresh autogeneic bone in cranioplasty followed the initial work of Kappis (1915) with whole ribs, Brown (1917) with split ribs, and Mauclaire (1914) with ilium (18, 46, 61). The histological sequence of autogeneic bone transplant repair was first fully documented by Axhausen in 1907, who described the process of invasion of blood vessels along preexisting channels followed by dynamic reconstructive processes of resorption and appositional new bone formation ("schleichender ersatz" translated "creeping substitution") (9).

Alloplastic repair of cranial defects has followed the availability of various plastics and metals through this past century. Celluloid used by Fraenkel in 1890 had an extensive trial but later was abandoned because of cellular reactions and biodegradative processes in tissue (18, 46, 61). Aluminum, one of the first metals used by Booth and Curtis in 1893, was soon followed by gold utilized succesfully by Gersten (1895) and more extensively tried by Estor (1916). Many metals subsequently have

had clinical trials including vitallium alloy (cobalt, chromium and molybdenum) used by Geib (1941), tantulum by Pudenz and Odom (1942) and Fulcher (1943), stainless steel mesh by Boldrey (1944), stainless steel by Scott, Wycis and Murtagh (1956), titanium by Simpson (1965) and Gordon and Blair (1974) (6, 53). Seven decades after its introduction, Black (1978) has returned to the use of aluminum because of its malleability, radiolucency and low tissue reactivity (5).

Acrylic resins became available as industrial materials in 1937. Under trade names of vitacrilic, lucite, plexiglass, crystallite, or cranioplastic, methyl methacrylate was introduced to human cranioplasty by Zander in October, 1940 (61). A one stage acrylic method described by Spence (1954) is now the most widely used method (50). Galicich and Hovind in 1967 found incorporating stainless steel mesh within the methyl methacrylate rendered it less brittle (15). More recently Habal, Leake and Maniscalco have reconstructed cranium with an alloplastic tray of polyurethane terephthalate (cured Dacron/urethrane composite) filled with autogeneic cancellous bone (22). Polyethylene introduced by Alexander and Dillard in 1950, has never achieved broad usage because of difficulties in obtaining a pure form (29, 53). Softness of silastic rubber has militated against its general use since first employed for cranioplasty by Courtemanche and Thompson in 1968 (11).

Over this past century the plethora of methods tried and latter abandoned for various reasons has paralleled the increasing need for a suitable implant. The incidence of trauma through wars and vehicular accidents and multiplying neurosurgical procedures has provided an experiential base upon which principles of cranioplasty have evolved.

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CAUSES OF SKULL DEFECTS; INDICATIONS FOR AND TIMING OF CRANIOPLASTY

Skull defects most commonly result from trauma. Contaminated compound depressed skull fractures among civilian and penetrating head injury among military personnel are the most frequent causes. More recently a defect resulting from a growing skull fracture has been found in children usually under 3 years with an antecedent usually parietal skull fracture within 4-6 months, and associated with a dural tear, cerebral herniation and ventricular dilatation and porencephaly (20, 30).

Skull defects also arise from excision of tumors (osteomas, hemangiomas, meningiomas, eosinophilic granulomas, epidermoids, metastatic cancer, fibrous dysplasia), infections (osteomyelitis, infected skull flaps), aseptic necrosis of skull flaps, radionecrosis and electrical burns of skull, congenital absences of skull (encephaloceles, large parietal foramina and other anomalies of the obelion). Cerebral swelling from brain tumors, trauma, infections, and lead intoxication at times requires external decompression and thereby results in a skull defect.

Defects larger than 2-3 centimeters over the cerebral convexity or less in the glabrous frontal areas are universally repaired. Exceptions to this general rule include deficient skull under temporalis or occipital muscles or calvarial discontinuity in the elderly or mentally encumbered. If cerebral seizures occur among these latter patients, a cranioplasty should be done to protect the brain.

Among the possible indications for cranioplasty the two commonly accepted ones address issues of cerebral protection and appearance. These two indications also partially delimit materials used to restore the integrity of the cranium. Although the relief of wound discomfort and seizures was once

thought to follow cranioplasty, these two consequences are no longer considered tenable. Neither is the "syndrome of the trephined" consisting of headaches, dizziness, intolerance of vibration and noise, irritability, fatigability, loss of motivation and concentration, depression and anxiety universally accepted as an indication to reconstruct the skull (19, 59). This last constellation of symptoms is regaining some credibility from recent reports which describe the effects of direct atmospheric pressure on the brain (14, 52). Both ventricular migration toward a small defect with a corresponding ipsilateral midline shift and contralateral shift of central structures under a large defect have been reported (30, 51, 52). Associated with this anatomical displacement of brain has been contralateral hemiplegia (Tabaddor and La Morgese, 1976) (52), increased intracranial pressure (Langfitt, 1968), hemispheric collapse (Stula and Müller, 1980) (51), and cerebrospinal hydrodynamic changes (Fodstad, Ekstedt and Friden, 1979) (14) in patients with large cranial defects. In these large defects with anatomical displacement of cerebral structures, the return of the patient to normal after cranioplasty was noted in each of the above reports.

Four pursuasive indications for cranioplasty, therefore, are restoration of cerebral protection and physical appearance, intracranial pressure relationships, and the provision of an intact vault for the normal growth and development of cephalic structures in the young. Evidence supportive of the organic basis of the "syndrome of the trephined" is the improvement in symptoms following cranioplasty with the reversion of intracranial pressure relationships to normal. Convulsive disorders and wound tenderness are unlikely to benefit from cranioplasty.

Contraindications to cranioplasty include the presence of hydrocephalus,

cerebral swelling, infection, a compound wound, contiguous functional paranasal sinuses (as indicated by air within a sinus on X-ray), thin scarred or devitalized scalp. Children under six will frequently regenerate skull provided dura is intact and not grafted. At least one year after craniectomy should elapse before considering cranioplasty in children.

Timing of cranioplasty is critical to avoid infection developing in devitalized autografts or alloplastic substances. It is generally accepted that cranioplasty should be delayed 3-6 months after compound wounds and at least one year after a wound infection. The report of Rish et al. in 1979 based on 491 cranioplasties performed by numerous neurosurgeons clearly established the desirability of waiting one year after penetrating or compound cranial injuries (47). The use of stainless steel mesh and antibiotic cover by Koslow and Ransohoff suggests an alternative method in rare and exceptional circumstances (32).

ATTRIBUTES OF IDEAL CRANIOPLASTIC MATERIAL

Most will agree that no alloplastic plate will ever exceed in quality the properties of viable full thickness autogeneic skull. That such tissue is quantitatively unavailable explains the search for an acceptable albeit imperfect substitute. An ideal material would be (1) viable and thereby capable of growth and resistance to infection, (2) radiolucent, (3) thermally nonconductive with a coefficient of expansion identical with surrounding skull, (4) non-ionizing or corrosive, (5) stable (durable, nonbiodegradable), (6) inert (nonreactive, nonantigenic, nonsensitizing, noncarcinogenic), (7) esthetically pleasing, (8) protective with equivalent

biomechanical properties compared to skull, (9) malleable, easily contoured, (10) inexpensive, (11) readily available, (12) sterilizable (13). For various reasons no present material satisfies all these criteria. Autogeneic bone (rib, ilium) removed from its blood supply slowly becomes viable and capable of growth and resistance to infection. The frequently unsatisfactory esthetic result (up to 50%) (31), the necessity to harvest and thereby violate another area of the body, and the tendency to resorb with compromised biomechanical properties all are disadvantages in the use of autogeneic rib or ilium.

Metals are strong, can be sterilized and do not require a second operation. However, they more often become infected, indent, conduct cold and heat, ionize, corrode, are difficult to shape and are ususally radiopaque.

Acrylic resins provide favorable properties including strength, esthetic qualities, inertness, availability, thermal nonconductivity, ease of application. The plate remains a foreign body, however, with attendant risks of infection, brittleness, and stationary size. With a pore size of 50μ, bacteria may colonize within the plate (21). Methyl methacrylate is well tolerated both for cranioplasty and aneuroplasty, (7, 8, 23) but macrophages aggregate around implants and methyl methacrylate particles have been found in the liver (21). No report of carcinoma or sarcoma has followed the use of any plastic, including polyethylene in humans, despite the reports in rats (40).

TECHNIQUE OF CRANIOPLASTY WITH METHYL METHACRYLATE

The use of methyl methacrylate has been widespread since Spence described the one-stage method in 1954 (50). The brittleness of this mate-

rial resulted in reports of fractures (26, 27), leading Galicich and Hovind to recommend embedding wire mesh within the plate during the autopolymerization process (15). Lake, Morin and Pitts confirmed the more favorable mechanical properties of methyl methacrylate strengthened by coarse wire mesh (33). The plate should be at least 5 mm thick, except over temporal regions or in children's skull (Figs. 1 and 2).

Preparation of patient

Because acrylic is a foreign body, some neurosurgeons will deliver preoperative antibiotics active against staphylococcus, and continue them for 48 hours postoperatively. All the hair over the scalp is clipped on the ward and the scalp is scrubbed with disinfectant soap several times. After induction of general anesthesia the entire head is shaven and then positioned with the plane of the skull defect horizontal in order later to facilitate molding of the congealing plastic (Figs. 1a and 1b).

Preparation of the wound

Scalp flaps must be designed to lie outside of the defect, behind the hairline, never parallel to previous wounds and scars, and with a broad base to accomodate the vascular supply to the area of skin within the flap. If an incision is made through the old scar, one must exercise great care to avoid incising the dura. The entire scalp flap is elevated cautiously to avoid penetrating the dura in areas where it is adherent to the scalp (Fig. 1c). Emphasis must be placed on maintaining full thickness of the scalp, especially where it will overlie the acrylic plate. The temporalis muscle is reflected off the dura. The pericranium surrounding the cranial defect should be incised and the margins of the defect demarcated by removing soft tissue down to the dura with a curette. A

3-5 mm ledge is then drilled along the entire circumference of the defect to the diploë with a high speed bur. This allows the edges of the acrylic plate to be recessed and provides a smooth contour and firm fixation. At least four drill holes are placed through the skull around the circumference of the defect for securing the plate (Fig. 1d).

Preparation and positioning the acrylic plate

Strips of bulk cotton soaked in saline and of variable thickness are laid over the dura within the defect to establish the desired contour over which the plate will be molded (Fig. 1e). This material also further protects the brain from thermal or chemical injury from the acrylic plate (2, 16, 37). Methylene blue or another marker is then used to outline the edges of the defect along the ledge. A sheet of paper is then placed over the defect and the outline of the defect is transposed on to the paper. This pattern is then superimposed on to coarse #20 of #24 guage foundation stainless steel wire mesh and an appropriate configuration of wire mesh prepared. The wire mesh is then contoured over the bulk cotton in the defect. Thin radial sectors may be cut into the mesh to help in bending the coarse wire mesh (Fig. 1e). Wire must be coarse enough to permit penetration by the methyl methacrylate. A clamp is used to open up holes in the wire at 2 cm intervals.

A sheet of polyethylene folded along one edge is laid over the defect. In between the two layers of the sheet, the contoured wire mesh is positioned. Liquid monomer (the catalyst) is then added to the powdered methacrylate polymer. This mixture is continuously stirred until its consistency is doughy (soft putty) at which time it is poured over the wire mesh in between the layers of polyethylene sheet. Enough methyl

methacrylate is mixed to form a plate at least 5 mm thick for the adult skull. The surgeon, assistant surgeon and nurse then firmly press with their fingers along the edges of the defect to establish the boundaries of the plate (Fig. 1f). Intermittent molding of the plate will smooth out irregularities and promote equal thickness. Because this autopolymerization process is exothermic, cold saline should be irrigated over the plate while it hardens (16, 37). Studies have shown the subdural temperatures to rise very little. When the plate solidifies enough to hold its shape, it is removed from its position over the defect at a time when the exothermic process peaks. The plate is then trimmed and irregularities are removed with a drill (Fig. 1g). In the areas of the previously placed holes in the wire mesh, the drill is used to create 3-5 mm openings in the plate. This allows egress of epidural fluid and fibrosis to occur through the plate, with the scalp eventually becoming adherent to it. Smaller drill holes are placed at four points along the edges of the plate opposite holes in the skull in order to secure the plate in position with #28 stainless steel wire (Fig. 1h). The high speed drill is then further used to remove any excrescences over the plate. Bulk cotton overlying the dura is removed before copious saline irrigation purges the wound of debris. The temporalis muscle, galea and skin are closed in layers (Fig. 1i).

The postoperative roentgenographic appearance of such a plate demonstrates the wire mesh separated by a margin of acrylic from the edge of the skull defect (Figs. 2a and 2b). The contour of such a plate should follow that of the brain. Otherwise, in striving for perfect symmetry of the skull, one risks excessive pressure on the brain. Stainless steel

wire mesh embedded within the acrylic plate imposes minimal artifact on the computed tomogram (Fig. 2c).

As an alternative to direct formation of an acrylic plate, some neurosurgeons prefer the prefabrication of such an implant by impression techniques in order to insure a good cosmetic result and reduce operating time. Maniscalco and Garcia (36), Jordan, et al, (28), Cooper, et al. (10) have described such procedures which require the services of a dental prosthetics laboratory. If the patient's own bone flap or that of another patient of identical cranial contour is available for use as a model, a plate may be prefabricated without estimating margins of the defect through the intact scalp (4). Asimacopoulos, et al. reported forming an impression and thereafter a plate of methyl methacrylate during the operative procedure to improve the cosmetic appearance and strength of the implant (2). The prefabrication techniques are most applicable for very large hemicraniectomy defects, where irregularities and low stress points in the plate may be eliminated (10, 28, 29, 36).

Methyl methacrylate is available from Codman (cranioplastic, Codman, Randolph, Massachusetts, 02368). Whereas aluminum wire mesh has the most favorable combination of strength properties, malleability, and radiolucency the Food and Drug Administration prevents its use. Most vendors now have stopped supplying stainless steel wire mesh, but implantable grade stainless steel wire mesh of various guages is available from Melrath Gasket, P.O. Box 9830, Philadelphia, Pennsylvania, 19140 (Telephone 215-223-6000).

TECHNIQUE OF AUTOGENEIC BONE CRANIOPLASTY

Despite the universal popularity of cranioplasty with methyl meth-

acrylate, there are indications for autogeneic bone grafting of skull defects (31, 34, 35, 38). In children undergoing active growth of brain and skull, autogeneic bone grafting is obviously advantageous because of the capacity of the bone to respond to developmental forces pari passu with surrounding skull. It has been shown further that viable bone is more resistant to infection. When an alloplastic plate must be removed in an adult because of infection, fracture, or hypersensitivity, then consideration must be given to the use of autogeneic rib or ilium. Although Kappis in 1915 used whole rib, it was Brown in 1917 who suggested splitting the rib to obtain greater volume of bone and more easily contour the autograft. Credit must be given to Longacre for emphasizing the clinical utility of autogeneic rib and providing a scientific base through studies in the monkey (35). He emphasized the unique osteogenic proliferative capacity of transplanted rib, the large reservoir of autogeneic ribs within the body and its regenerative character. If its thoracic periosteal bed is preserved, rib regenerates within five weeks in the young child and if necessary may be used again for transplantation. McClintock and Dingman (53) reported the successful use of iliac bone for cranioplasty in 1951 even before the studies of Longacre.

Two operative fields are necessary for autogeneic bone cranioplasty (Figs.3b and 3e). The source of autogeneic bone for smaller defects may be the iliac crest. For larger defects the rib grafts should be employed. Incisions for rib grafts are made to take some alternate combination of ribs (e.g. ribs 4 and 6). The thoracic incision is curved posteriorly to allow exposure of more ribs. An incision is made through the periosteum overlying the rib and as much rib as possible is removed from the

transverse process to the costal cartilage.

An estimate of the total length of rib needed is determined by the formula $L = \frac{A}{Wx2}$, where L is the length of the rib required in centimeters, A is the surface area of the defect in square centimeters, and W is the average width of the rib in centimeters (38). Ribs are cut 4 mm longer than the defect. The costal periosteum is then closed with 000 catgut suture. If the pleural cavity is entered, closure should be effected at time of Valsalva maneuver. The chest wall is then closed.

The cranial wound is prepared in the same manner described above for alloplastic cranioplasty (Fig. 3c). In this case, however, the eburnated margins of the defect must be curetted and ridded of fibrous tissue back to bleeding bone (Fig. 3d). The high speed drill may destroy cells by heat production. It and the use of bone wax should be avoided. Either a 1 cm ledge is created along the edge of the defect on which to inlay the rib, or a groove may be tunneled between the inner and outer tables of the skull to position the tapered ends of the ribs (Fig 3g). The ribs are split with osteotomes (Fig. 3f) and contoured with strong clamps or bone benders to provide a suitable cosmetic result (Fig. 3g). It is extremely important that the sections of rib be firmly secured to the exposed cortico-cancellous bone at the margins of the defect. Contact compression forces at the junction between autograft and host skull ultimately determine whether the grafts will become viable or subsequently will resorb. The inlaid ribs are then secured at either end with #28 stainless steel wire (Fig. 3h). Adjacent ribs have either cortical or medullary surfaces facing the dura. Adjacent ribs must be closely approximated to one another

to stimulate osseous rather than fibrous union. Wiring adjacent ribs together has even been suggested in the manner of a chain linked fence (38). The wound is closed in layers as described above and a mild compressive dressing applied.

COMPLICATIONS AND RESULTS

Complications from cranioplasty may be divided among those characteristic of the operative procedure in general and those more related to the type of implant used. The risks for life in a patient with marginal cardiopulmonary reserve who is bedridden or sedentary are extraordinary when considering a procedure designed for cerebral protection and appearance. Death may occur if a large prefabricated plate does not follow the cranial contours and results in compression of the underlying brain and internal herniation. Infection in a plate with subsequent meningitis or cerebral abscess formation may lead to permanent morbidity or even death. A frequent instructive comment by all authors is the need to obliterate contiguous paranasal sinuses months before implanting any plate. Otherwise the alloplastic material or devitalized autogeneic bone are subject to external microbial colonization (23).

Metallic and plastic plates are foreign bodies which become encapsulated by host tissue. Sinus tracts between plate and skin, granulomas, and pneumatoceles have been reported (53). Plates may loosen and erode the skin. Acrylic plates, especially brittle unless they are fortified with stainless steel mesh, may fracture and injure the underlying brain or protrude through the skin. Infection remains the predominant concern for all foreign bodies, which then must be removed. Autogeneic bone grafts

are initially nonviable and therefore are subject to infection. These grafts later may resorb or lead to cosmetically undesirable ridges.

The mortality rate for cranioplasty is very low. Even before the modern era, Grant and Norcross reported a mortality rate of 0.73% among 1385 reported cases (18). Whereas complications of cranioplasty with tantalum were relatively frequent (60), a much more favorable experience with methyl methacrylate has been apparent. Infection rates usually range between 1-8% (23, 47, 54, 63), with an inexplicably high rate of 12% in one report (41). Hammon and Kempe reported 1% infection, 2% morbidity and no mortality among 417 cranioplasties at the Walter Reed General Hospital (23). The most comprehensive survey of 491 cranioplasties performed by many surgeons was published by Rish, et al. in 1979 (47). Their mortality rate of 0.2% with total morbidity of 5.5% (infection rate of 3.7%, plate loss 3.1%) is likely representative of the results achievable in the community practice of neurosurgery.

Through the past 40 years of usage there have been no reports of malignancy associated with implanting acrylic resin, and the plastic is well tolerated by the adjoining tissue (7,8). In general the cosmetic result with methyl methacrylate is favorable, though large plates may give the head a flattened appearance, and wire mesh must be imbedded to prevent fracture of these brittle protheses.

Autogeneic bone is preferred by many, especially in children and generally in areas of previous infections or adjacent to sinuses (18, 31, 34, 35, 41, 48). Among 55 cranioplasties with autogeneic bone (46 rib, 9 ilium), Korloff in 1973 reported 1 infection (31). The cosmetic result was satisfactory in only 50% of these cases, however. Petty (1974) reported

no infections in 19 rib cranioplasties with only 1 case of resorption (41). Leivy and Tovi (1970)reported no complications among 9 patients (7 rib, 2 ilium (34). With the use of osteoperiosteal grafts of skull Grant and Norcross (1939) reported an infection rate of 5.1% among 89 cases (75 osteoperiosteal, 7 rib, etc.). They recommended use of 7th and 9th ribs for defects larger than 6 x 6 cm in size (18). Santoni-Rugiu (1969) transplanted 12 osteoperiosteal grafts from adjacent cranium without complications (48).

General disinclinations to use autogeneic bone among many neurosurgeons result from the need for two operative fields, more operative time, difficulty sculpturing the autograft, some tendency for the grafts to resorb, donor wound complications (pain, pneumthorax), and the frequently unacceptable cosmetic result.

PRESERVATION AND DELAYED REIMPLANTATION OF SKULL FLAPS

Sections of cranium are often exteriorized for various periods of time with the prospect of delayed reimplantation. Treatment of skull after removal determines in large part its natural history after replacement. Odom and Woodhall (1952) (39) and Abbott (1953) (1) reported success with delayed cranioplasty after freezing the autograft. Hancock (1963) cautioned against autoclaving exteriorized skull because of the high rate of aseptic necrosis and infection with these replaced frozen autografts (24). Fresh bone separated from its blood supply dies, with the exception of some periosteal, endosteal, and medullary cells and osteocytes within 0.2 mm of cortical bone surfaces. Frozen bone is entirely devitalized. The reorganization of a dead bone plate requires revascularization followed by resorption of dead bone trabeculae and

cortex, then finally appositional new bone formation (42). After bone is frozen, there is impaired coupling of new bone formation to follow the initial resorptive phase.

At this time the only generally accepted method of preserving cranium is by freezing to -70° C or freeze-drying after aseptic removal from the skull. The extent of resorption within these frozen plates is considerable in many and not reduced even by augmentation with fresh corticocancellous bone. Some of these frozen plates must be later removed and an acrylic cranioplasty performed if resorptive processes leave a thin, unprotective and cosmetically undesirable plate. The length of time the cranium is frozen has no bearing on the outcome; neither does sterilization with ethylene oxide adversely effect the biological events in the replaced plate (43). Despite this tendency toward resorption, restoration of skull with frozen autogeneic skull is generally successful, except in individuals under 13 (24). In younger people with very thin cranium, resorption reduces the replaced plate to only a small remnant.

In an effort to prevent resorption of an externalized plate, many clinicians have tried novel approaches for cranial bone preservation. Kreider (1920) and more recently Hauptli and Segantini (1980) have implanted the skull section subcutaneously in the abdomen (25, 46). This technique would likely maintain viability of some superficial cells and perhaps some matrix proteins. Yamada et al. advocated coating the exteriorized bone graft with acrylic resin to reduce resorption, but report an infection rate of 11% (62).

Skull which is contaminated may never be boiled or autoclaved without denaturation of the essential bone proteins (and resultant nearly universal resorption). Cold cycle ethylene oxide may be used to sterilize skull provided

residues are desorbed by lyophilization or prolonged aeration over at least five days at room temperature (44).

The fresh autograft of skull remains the best graft. No preservative method for bone yet equals the osteogenic capacity of a fresh autograft (43). That such a graft is unavailable accounts for the search for a suitable alternative.

PROSPECTS FOR THE FUTURE

Calvarial bone has the lowest regenerative capacity of any bone within the body. This characteristic led Barth (1893-1898) to conclude in error that all fresh transplanted bone dies and must be replaced by surrounding tissues (9). It is known that fractures of the cranial base (of chondral origin) heal faster than those over the convexity (of membranous origin) (35).

In an elegant series of experiments in growing rabbits, Uddströmer (1978) demonstrated the inherent deficiency of periosteum from skull to form bone (55, 56). Isolated periosteum of tibia over tibial defects had 7 times the potency for osteogenesis compared to skull periosteum placed over skull defects. Tibial periosteum transplanted over skull defects reproduced calvarial-like bone and skull periosteum placed over tibial defects increased its osteogenic capacity five-fold. It may be concluded that environmental functional demands influence the type of bone formation and final structure, but there are intrinsic differences between long and membranous bone periosteum in the amount of bone formed.

It is possible that in the adult skull, the diminished functional demands and stresses (Wolff's law) results in the predominance of

resorption over appositional new bone formation in the implant. There are further biological differences in the proliferative capacities of living periosteum derived from bone of cartilaginous versus that of membranous origin. Bone modified by physical (boiling, freezing, irradiation) and chemical treatments further must lose structural proteins which ordinarily enhance new bone formation at the recipient site.

Bone is one of the few organs in the body which retains the primordial capacity to induce regeneration of lost parts. A bone morphogenetic hydrophobic glycoprotein has been characterized of low molecular weight (58). This "bone morphogenetic protein" induces cell differentiation in perivascular mesenchymal and other undifferentiated cells. More recently a human skeletal growth factor isolated from demineralized adult human bone matrix has been shown to increase the proliferation rate of embryonic chick bone cells in culture (12). This mitogen putatively released from resorbing bone is postulated to couple bone resorption to formation by interacting locally and selectively with osteoblastic progenitor cells, thereby regulating the amount of bone formed.

Senn in 1889 reported demineralized bovine bone to have some osteogenic capacity. More recently Shehadi (1970) and Bakamjian and Leonard (1977) reported the osteogenic capacity of demineralized bone (3, 49). Experimental and clinical studies confirm the well established findings of Urist, Reddi, and others that demineralized bone is osteogenic (17, 45, 57).

In the future research will be directed at characterizing and preserving osteogenic factors in bone and maximizing conditions at the bone

graft site that promote appositional new bone formation. An implant of human bone for cranioplasty at once conveying immediate protection to the brain, reconstructing symmetrical contours for the head, and capable of undergoing revitalization with prospects for evolutionary viability is the goal for the future.

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Fig. 1 Methyl Methacrylate Cranioplasty. Acrylic cranioplasty lends itself to all regions of the skull except in areas of infection or in direct contiguity with functional paranasal sinuses. (a) At operation the head is positioned with the plane of the defect horizontal to facilitate later molding of the hardening plastic. (b) A scalp incision is outlined on the skin outside the area of the defect and infiltrated with a local anesthetic containing adrenalin. (c) Margins of the defect are defined with removal of soft tissue down to the dura and with avoidance of penetrating this protective membrane. (d) A 5 mm ledge is carved with a drill around the defect. At least four holes are placed around the defect. (e) Bulk cotton is placed over the dura to approximate the normal cranial contour. Methylene blue is traced over the ledge. This outline is then transferred on to paper spread over the defect. A paper pattern of the defect is then placed over #20 guage stainless steel wire mesh, and the wire mesh is cut in the shape of the defect. Sectors are cut out of the wire mesh to facilitate bending it, and 5 mm holes are opened up in the mesh with a small clamp. (f) Enough acrylic monomer and polymer are mixed to provide for a 5 mm thick plate. The wire mesh and acrylic of doughy consistency are placed within a folded plastic sheet that is positioned over the defect. At least 3 pairs of hands are positioned around the defect to fashion a plate of desired shape and thickness. (g) Excrescences are removed with a bur and holes are drilled around the edges of the plate to secure it to the skull and through the interior of the plate to allow for escape of extradural fluid and penetration of binding fibroblasts. (h) The plate is secured with #28 stainless steel wire and the wound closed (i).

Fig. 2a Lateral skull x-ray of methyl methacrylate-stainless steel wire mesh plate. Wire mesh does not reach margins of the defect and is surrounded by and embedded within a five mm thick acrylic plate. A diversionary shunt done nine months previously for communicating hydrocephalus is seen.

Fig. 2b Anterior-posterior skull x-ray shows acrylic-mesh cranioplasty. Rim of acrylic surrounds mesh. Child's head is asymmetrical from hydrocephalus and disturbed cranial growth after severe injury with cerebral swelling and an acute subdural hematoma.

Fig. 2c Computed axial tomogram of same two year old patient shows brain reaching inner portion of the acrylic-mesh plate, some artifact from the wire mesh, and evidence for treated communicating hydrocephalus.

Fig. 3 Autogeneic Rib Cranioplasty. (a) Autogeneic rib cranioplasty is indicated in defects previously infected or contiguous with paranasal sinuses and by some neurosurgeons in children. (b) The scalp incision is made behind the hairline and never directly over the defect. (c) The skull defect is exposed with removal of all soft tissue from the margins of the defect to the dura. A curette is used to fashion a ledge (d) or a groove (g) for inlaying the tapered ends of the rib. (e) Alternate ribs are removed and (f) split with an osteotome after a groove is made along one edge. (h) Split thickness ribs are placed across the defect with alternate medullary or cortical surfaces facing the dura. Ribs are stabilized in position with #28 stainless steel wire at each end and also across the middle with interlocking wire to hold the ribs in tight contact and thus stimulate bony union.

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